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Outer- to inner-shelf response to stepped sea-level rise: Insights from incised valleys and

2 submerged shorelines

3

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11

12 Abstract

13 Shorelines respond to rising sea-level through processes such as erosion,
landward migration

14 and in-situ drowning (i.e. overstepping). Submerged and preserved shorelines
on the

15 continental shelf play a key role in examining coastal response to rising sea
levels as they

16 provide important information on how modern shorelines may evolve in time
and space within

17 the context of changing climate and post-glacial sea-level rise. This study
identifies and

18 assesses the response of a continental shelf to stepped rises in sea level with
particular focus

19 on the stepwise evolution of incised valleys and shorelines from the shelf-edge
to the inner

20 shelf. Multibeam bathymetry data from the mid-outer allow for the analysis of
seafloor

21 morphology, including the Protea Banks Reef (a palaeo-shoreline complex),
and the adjacent

22 incised, sediment starved continental shelf. Six seismic units and intervening
surfaces are

23 identified using interpretations from sub-bottom profiles, these include the
incised acoustic

2

24 basement, variable incised valley fill successions, aeolianite ridges and post-
transgressive

25 shoreface and associated sediments that withstood wave ravinement
processes. The incised

26 valleys of the outer-shelf are manifested as distinctive seafloor depressions,
filled at their bases

27 by fluvial deposits overlain, in the unfilled valley, by deposits derived from
cascading

28 subaqueous dunes which comprise the upper-most post-transgressive
sediments. A core

29 intersecting the dune material yields a maximum age of deposition of

12751191 - 1263 cal. yr

30 B.P, BP (68% range), synchronous with a period of higher than present sea-
levels in the region

31 suggesting reworking and redistribution of coastal sediment as shelf sediment
post-

32 transgression. During the stepped rises in sea level, the shoreface has
disconnected from the

33 contemporary shoreline and is preserved by means of topographic barriers
formed by

34 antecedent topography as relict shoreface deposits. We provide a new
perspective of shoreline

35 response to stepped rises in sea level by integrating the seismic architecture
of incised valley

36 fills and shorelines across the continental shelf thus allowing for the
assessment of variation in

37 rates of relative sea-level rise since the last glacial maximum.

38 **Keywords**

39 Shoreline Palaeo-shorelines, Preservation potential, Shoreface, Incised-valley,
Overstepping

40

41 **Highlights**

42 □ Unfilled incised-valleys during transgression because of a lack of sediment and/or
an increase
43 in accommodation space associated with a rapid increase in sea level.
44 □ Confinement points created by aeolianite barriers on the outer-shelf prevent
sediment
45 stripping by the Agulhas current, suggesting antecedent controls on the
preservation of
46 shoreline deposits.
47 □ Preservation of shoreline barriers by overstepping is related to the ensuing
meltwater
48 pulses 1A and 1B.

3

49 □ During the stepped rises in sea level, the shoreface has disconnected from
the
50 contemporary shoreline.
51 □ A reduction of sediment supply for back-barrier/beach and shoreface
exchange during
52 subsequent shoreline construction could lead to increased rates of shoreline
retreat and
53 potentially overstepping of low-lying coastal areas.

54

55

56 **Introduction**

57 Barriers and associated shorelines respond to sea-level rise by three
archetypal processes.
58 These include an erosional response, landward migration in step with sea-level
rise, or
59 overstepping of the shoreline and in-situ drowning of the shoreline deposits
(Cattaneo and
60 Steel, 2003; Cooper et al., 2018a). In the context of globally rising sea-levels
and associated
61 risks from erosion and coastal inundation (e.g. Saito 2001; Thanh et al. 2004;
Gibbons and
62 Nicholls 2006; Blum and Roberts 2009), significant planning to mitigate the
future economic,

63 environmental and social impacts of such “coastal squeeze” (Mellet et al.,
64 2018) needs to be
65 made. The understanding of shoreline behaviour under past and future
66 conditions of sea-level
67 change can be assisted by investigations of Holocene shoreline deposits on
68 the continental
69 shelf.
70 Submerged and preserved shorelines of the seafloor play a key role in
71 examining coastal
72 response to rising sea levels. Their preservation in relation to antecedent
73 gradient (Green et al.,
74 2018), rates of sea-level rise (Locker et al., 1996; Green et al., 2014) and
75 sediment supply
76 (Mellet et al., 2012) relay important information on how modern shorelines
77 may evolve in time
78 and space in the context of changing climate and post glacial sea-level rise.
79 4
80 The postglacial evolution of submerged shorelines has received much recent
81 attention (Gardner
82 et al., 2007; Storms et al., 2008; Maselli et al., 2011; Green et al., 2012, 2013a;
83 Mellett et al.,
84 2012; Salzmann et al., 2013; Pretorius et al., 2016) and has been shown to be
85 intimately linked
86 to stepped rises in sea level throughout the Late Pleistocene to Holocene.
87 Shoreline-associated
88 and co-occurring shoreface and incised valley deposits also provide valuable
89 information on
90 the evolution of coastal systems during and after transgression. This study
91 thus aims to identify
92 and assess the response of In particular, shelf-hosted incised valley systems
93 may hold important
94 clues to the relative balance between postglacial rises in sea level and
95 available sediment. In
96 this regard, Cooper et al. (2012) proposed a tripartite classification scheme for
97 incised valleys.

81 “Keep-up” incised valleys maintain infilling in pace with rising sea level, as
such their fills are
82 mostly uniform sands. As Cooper et al. (2012) state “Such ‘keep-up’ estuaries
are
83 comparatively rare and occur only where conditions of high sediment supply
kept pace with
84 the very high rates of sea-level rise in the early to mid-Holocene”. “Catch-up”
incised valleys
85 form when sea-level rises initially outpace sediment inputs, with a deep
system forming, then
86 later, during stable or slower rising sea levels, the system fills with marine or
fluvial materials.
87 The last example is the “give-up” system. Here, sea level increases as a rate
significantly
88 greater than can be balanced by sediment supply and the system is effectively
drowned. There
89 is insufficient sediment to produce an incised valley fill, or the classic
“sediment sandwich” of
90 Ashley and Sheridan (1994). Give-up systems thus point to situations where
sea-level rise has
91 been dramatic, or there has been a significant reduction in sediment from
either marine or
92 fluvial sources.
93 Using a series of newly discovered submerged shorelines and multiple give-up,
or underfilled
94 incised valleys exposed on the seafloor, we examine the shelf morphology and
stratigraphy of
95 a portion of current-swept shelf from the South African margin. By virtue of the
high levels
96 of preservation of these geomorphic forms on the shelf, we aim to identify and
assess the
5
97 response of such a shelf to stepped rises in sea level. In particular, we focus
on the stepwise

98 evolution of incised valleys and shorelines from the shelf-edge to the inner shelf; and consider

99 the general evolution of the associated shoreface in this regard.

100

101 **2. Regional Setting**

102 The southern KwaZulu-Natal continental shelf is narrow (~8 km) and steep (~0.6°) when

103 compared to global averages (75 km and 0.1°, 1°, respectively) (Shepard, 1963). The shelf

104 break occurs at ~100 m water depth and marks the transition from the continental shelf to the

105 upper-continental slope (Fig. 1) (Green et al., 2013a).

106 The KwaZulu-Natal coastline is wave-dominated throughout the year, with a significant wave

107 height of 1.8 m (Moes and Rossouw, 2008). The coastline is upper microtidal with a spring

108 tidal range of 1.8 m (Moes and Rossouw, 2008). The continental shelf is swept by the poleward

109 flowing Agulhas current which accounts for the overall sediment starved nature of the shelf

110 (Fig. 1) (Martin and Flemming, 1988; Green and McKay, 2016).

111 The acoustic basement of most of KwaZulu-Natal comprises seaward prograding Cretaceous-

112 aged siltstones which can be traced north to the central and northern KwaZulu-Natal

113 continental shelf (Green and Garlick, 2011; Cawthra et al., 2012; Green et al., 2013a; Salzmann

114 et al., 2013). The shelf has been incised by a network of valleys during past lowstand events

115 (Green et al., 2013b) the most recent of which was the Last Glacial Maximum (LGM) of

116 ~18 000 yr BP when sea-level was ~120 m below present (Fig. 11) (Cooper et al., 2018b). The

117 contemporary coast contains the estuaries of the Mzumbe and

MzimkuluUmzimkulu rivers,

118 whose seaward extensions can be traced offshore as incised valleys.

6

119 Overlying the Cretaceous siltstones is Protea Banks, comprising a set of positive seabed

120 features with ridges whose crests occur at depths of >30 m in the southern portion of the study

121 area (Fig. 1). ~~the~~The surface morphology includes linear ridges and parabolic plan forms.

122 These features correspond to areas north of the study area, where several shore-parallel ridge

123 features composed of aeolianite and beach rock material that represent former shoreline

124 occupations (Green et al., 2014) occur and are considered to be late Pleistocene-Holocene in

125 age (Martin and Flemming, 1987). The overall topography of the seafloor is rugged and uneven

126 with a gentle seaward dipping gradient of 0.2° . The shelf break is linear and occurs at ~100 m

127 water depth.

128 A discontinuous sediment wedge drapes the shelf and its surface features, with Cretaceous

129 siltstones sub-cropping a winnowed gravel pavement on the outer-shelf edge (Flemming,

130 1980).

131

132 **3. Materials and Methods**

133 Bathymetric data were collected using a WASSP WMB 3250 multibeam sonar system.

134 Accurate positioning (<30 cm RMS horizontal) was achieved using a Hemisphere VS330 Real

135 Time Kinematic (RTK) and heading system, with the RTK base correction. Motion correction

136 was applied by a xSens MTi-G motion reference unit mounted at the WMB 3250 transducer.

137 Sound velocity profiles were collected with a Valeport MiniSVP. The
bathymetric data were
138 corrected with RTK tides with an averaging of 300 seconds. The multibeam
data were then
139 post-processed employing a three-step procedure including: 1) Processing of
navigation data
140 for movement and physical properties of the water column such as roll, pitch,
heave, tide, draft
141 and sound velocity; 2) Operator based processing, manual removal of artefact
data points; 3)
142 Application of CUBE™ filter and TIN (Triangular Irregular Networks) using
HypackTM
7
143 software. TheseThe data were manually inspected, and point removal was
carried out. The final
144 bathymetric colour image map was produced using Golden Software Surfer 12
withthen
145 exported as a data resolution of 102 x 102 m grid.
146 High-resolution seismic profiles were collected using a 200J sub-bottom
profilerApplied
147 Acoustics boomer, coupled to an 18-element hydrophone array. The data
were collected and
148 processed using HypackTM software that included the application of time-
varied gains, band-
149 pass filtering (300–1200 Hz), swell filtering, and manual seabed tracking.
Streamer layback
150 and antenna offset corrections were applied to the digitized data set, and
constant sound
151 velocities in water (1500 m/s) and sediment (1600 m/s) were used to
extrapolate all time-depth
152 conversions. The vertical resolution of these data is ~5070 cm. (Brown, 2011).
Ultra high-
153 resolution seismic profiles were collected using a PARASOUND parametric
echosounder

154 aboard the RV Meteor, during cruise M123. The low frequency output (3.5
kHz) was selected
155 due to signal attenuation of the higher-frequency spectra. The data were de-
spiked and match-
156 filtered, and the envelope data exported in SEG Y format for visualization in
HypackTM. These
157 data resolve to ~10 cm in the vertical domain. (Brown, 2011).
158 A four metre-long core (GeoB20622-2) was acquired, from location 30°45.301'S;
30°35.520'E at
159 a depth of ~80 m below mean sea level, aboard the Meteor RV M123 cruise.
An initial report
160 on the main sediment features can be found in order to examine the cruise
report published by
161 Zabel (2016). The sediment core allowed for the examination of the sub-
surface stratigraphy
162 of the study area and to conduct ground-truthing of the seismic results. The
core was collected
163 using a 100-mm-diameter, five metre-long marine vibro-corer from a water
depth of 90 m (Fig.
164 1). The cores were split into archive and working halves, scanned immediately
after opening
165 using a smartcube© camera image scanner capturing high resolution digital
photographs, and
166 logged according to standard Indian Ocean Drilling Project (IODP) GeoB
sedimentological
167 procedures. The core was sub-sampled for AMS C₁₄ dating, microfossils and
grain size
8
168 analyses. The AMS C₁₄ dates were calibrated using OXCAL software (Ramsey,
2001) and the
169 marine13.14c calibration model (Reimer et al. 2013). The marine ΔR is
assumed to be 121 ± 16
170 ¹⁴C yr (Maboya et al. 2017). Despite there being 4 m worth of core material,
only one intact

171 bivalve was discovered. Datable materials (such as life-position articulated bivalves)

172 accumulating in wave-dominated and current-swept shelves are notoriously difficult to find

173 due to the extent of reworking of the substrate. Furthermore, the high energies preclude the

174 accumulation of organic-muds, most of the sediments are considered palimpsest (Flemming,

175 1980).

176 Grain size analyses at 5cm intervals downcore were performed at the Center for Marine

177 Environmental Sciences (MARUM) in Bremen, Germany, using standard laser diffraction

178 analysis.a Coulter LS-13320 machine. The samples were pre-treated prior to analysis removing

179 organic and carbonate fractions. The grain size analysis measured grain size contents in 117

180 classes which ranged from 0.04 to 2000 μm as a volume percent (vol%).

GRADISTAT

181 software (Blott and Pye, 2001) after the Folk and Ward (1957) method were used to calculate

182 the first moment statistics.

183 **4. Results**

184 **4.1. Seismic stratigraphy**

185 Six units and intervening surfaces were identified using interpretations from ~67 line-km ultra-

186 high resolution PARASOUNDthe sub-bottom profiles and 104 line-km 200 J, 600 Hz high

187 resolution sub-bottom profiles (Fig. 1).. A summary of the seismic facies and intervening

188 surfaces is indicated byprovided in Table 1.

189 Unit 1

190 This unit is uncommon and was evident only in two shore perpendicular section extending off

191 the southern headland of the Umzimkulu River (Figs. 2 and 3). Unit 1 is
acoustically opaque.

9

192 The upper limit of Unit 1 is marked by a very high amplitude, undulating
reflector (Surface 1)

193 (Fig. 2).

194 Unit 2

195 Unit 2 downlaps Unit 1 forming an unconformity, Surface 1 (Fig. 2). This unit
is subdivided

196 into two sub-units based on varying dip angle:

197 Unit 2.1.

198 Unit 2.1 comprises seaward dipping (12.5°), moderate to low amplitude,
prograding reflectors.

199 This unit crops out at the sea floor from the inner-shelf to mid-shelf and is
planed off and

200 incised by Surface 2 (Fig. 3). Unit 2.1 is unconformably overlain by Unit 2.2 at
its most seaward

201 extent in the mid-shelf (Figs. 2 and 3).

202 Unit 2.2.

203 **Similar to** Like Unit 2.1., Unit 2.2 comprises moderate to low amplitude,
seaward prograding

204 reflectors that dip at a steeper angle ($\sim 20^\circ$) (Fig. 3). This unit crops out on
the seafloor from

205 the mid-shelf to the shelf edge (Figs. 3 and 4). Unit 2.2 is similarly truncated
and incised across

206 the entire shelf by Surface 2.

207 Unit 3

208 Unit 3 comprises moderate to high amplitude, prograding seismic reflectors
(Fig. 5a). This unit

209 **is isolated in occurrence does not frequently occur** and **when it does, it occurs**
in association

210 with Unit 6.1. It directly onlaps the acoustic basement within topographic
depressions

211 occurring from the mid-shelf to outer-shelf and is planed off by a moderate to
high amplitude

212 seismic reflector/surface, Surface 3.

213 Unit 4

10

214 Unit 4 can be subdivided into three sub-units. Unit 4.1 comprises moderate amplitude,

215 prograding reflectors that onlap Surface 2 (Figs. 2c, 3b, 4a and 4c). Unit 4.1 occurs at the base

216 of incisions in Surface 2 and is capped by Surface 4. Unit 4.2 comprises either steep, larger-

217 scale, moderate amplitude, prograding seismic reflectors; moderate amplitude, seismic

218 reflectors onlapping Surface 2 (Figs. 2c, 3b, 4a and 4c); or poorly-developed, moderate

219 amplitude, discontinuous and chaotic seismic reflectors (Fig. 2b). Unit 4.3 is not always present

220 in the study area (Figs. 2b and 4a). Where it does occur, Unit 4.3 is separated from Unit 4.2 by a

221 gently dipping, high amplitude erosional seismic reflector (Surface 5) and onlaps units 2 and

222 4.2 (Figs. 2c, 3b, 4a and 4c). Unit 4.3 is composed of horizontal, subparallel to chaotic,

223 discontinuous seismic reflectors (Figs. 2c, 3b, 4a and 4c). In cases where the incisions of

224 Surface 2 are less wide and deep, Unit 4 appears massive with a poorly developed internal

225 structure (e.g. Figs. 2b and 6b, 7b). Unit 4 is truncated by a high amplitude, flat lying erosional

226 reflector, Surface 6, which merges with Surfaces 2, 3 and 5 to form a composite erosional

227 surface 2/3/5/6 (Fig. 4c).

228 Unit 5

229 This rugged unit crops out on the sea floor and is acoustically opaque, with no internal seismic

230 configuration (Figs. 2a, 3a, 5b, 5c and 7a). It is most abundant in the southern portion of the

231 study area and crops out in the mid-shelf to outer-shelf region at depths of 40
m and greater.

232 Unit 5 is strongly associated with Unit 6.2 as it is often onlapped by Unit 6.2
(Figs. 2c, 3a, 2c,

233 5b, 5c and 7a). Where Unit 5 sub-crops, it is capped by a very high amplitude
seismic reflector,

234 Surface 67, that in some localities crops out as part of the sea floor (Fig. 7a).

235 Unit 6

236 Unit 6 can be subdivided into three sub-facies based on their seismic
character and distribution

237 on the shelf. Unit 6.1. consists of moderate to low amplitude, continuous,
semi-parallel seismic

11

238 reflectors and onlaps the combined surface of 2/4 (Figs. 3b, 4c, 5a, 6a and
7b). From the ultra-

239 high resolution seismic data, the reflectors are arranged in a semi-parallel
configuration (Figs.

240 3b, 4c, 5a, 6a and 7b). This unit is most often situated in the in-shore portion
of the shelf (Figs.

241 2, 3b, 4, 5a, 6 and 7). Unit 6.2. rests within depressions of Surface 5 and
comprises moderate

242 amplitude onlapping, occasionally chaotic, discontinuous seismic reflectors
(Fig. 2a, 3a, 4a, 5b

243 and 5c). This unit has a semi-opaque and occasionally shingled internal
character and is capped

244 by Surface 78 (Fig. 7a). Figure 5b shows the weak development of seaward-
oblique prograding

245 foresets in subunit Unit 6.2. Unit 6.3. is present mainly in the mid-shelf region
(Figs. 2c, 3a, 4a,

246 4b, 5a, 5b and 7a). It is characterized by moderate amplitude, finely mottled
reflector packages

247 with larger scale bedding planes. This unit has an average thickness of ~4 m
but can reach up

248 to ~7 m thick within the topographical troughs formed by Unit 5 (Fig. 7a).

249 Table 1. A summary of seismic stratigraphic units, separating stratal surfaces
and, interpreted

250 depositional environments and stratigraphic ages.

Unit/

Sub-unit

Overlying

Surface

Seismic Description Interpretation of Depositional

Environment

U1 Acoustically opaque Granite-gneiss complexe of the Namaqua-
Natal Metamorphic Province (Cornell et
al., 2006)

S1 High amplitude, undulating Sequence Boundary (SB)

SU2.1 Seaward dipping ($\sim 12.5^\circ$), low
amplitude, prograding

Siltstone

S2 Maximum Flooding Surface (MFS)

(Green and Garlick, 2011)

SU2.2 Seaward dipping ($\sim 20^\circ$), low
amplitude, prograding

Siltstone (Green and Garlick, 2011)

S3 High amplitude, truncates and
incises Unit 2

Sequence Boundary (SB1) (Green and
Garlick, 2011)

3 Isolated, onlapping high
amplitude, prograding

Relict shallow near-shore facies (Green,
2011)

S4 Moderate to high amplitude Sequence Boundary?

SU4.1 Onlaps S2, moderate amplitude,
prograding

Fluvial lag

12

S5 Low to moderate amplitude Transgressive surface (Ts) (Nummendaal
and Swift, 1987)

SU4.2 Onlaps S2, steep, moderate

amplitude, prograding
 Central basin-fill (Zaitlin et al., 1994;
 Green et al., 2013b; Allen and
 Posamentier, 1994)
 S6 High amplitude, uneven Tidal ravinement surface (TRs)
 SU4.3 Horizontal, sub-parallel to
 chaotic discontinuous,
 retrograding
 Sandy estuarine barrier (Cooper, 2001;
 Nordfjord et al., 2006; Green et al.,
 2013b)
 S6 Very high amplitude, rugged Wave ravinement surface (WRS)
 5 Acoustically opaque, crops out
 on sea-floor
 Aeolianite barriers (Green and Garlick,
 2011)
 S6 Same as above -
 SU6.1 Moderate to low amplitude,
 continuous, semi-parallel
 Contemporary shoreface (Martin and
 Flemming, 1986)
 SU6.2 Onlapping, moderate amplitude,
 occasionally chaotic,
 discontinuous, semi-opaque,
 shingled, weakly seaward
 oblique prograding
 Palaeo-shoreface (Martin and Flemming,
 1986)
 S7 Weakly visible, low amplitude FS?
 SU6.3 Moderate amplitude, finely
 mottled, larger scale bedding
 planes
 Pebble-floored coarse sand with
 bioclastics. Shelf dunes, highstand
 sediment (Flemming, 1980; Green, 2009)

251

252 4.2. Seafloor morphology

253 Multibeam bathymetry of the mid-outer shelf provides additional information
on the seafloor

254 morphology including the Protea Banks Reef portion and incised continental
shelf.

255 The outer shelf comprises a series of alternating linear, shore parallel,
arcuate and ridge features

256 occurring at 60 m and 100 m depth. These ridge features have ~5-10 m relief
above the sea

257 floor (Figs. 8b and 8c), and in some areas exist as multiple parallel ridges over
a distance

258 spanning 200-300 m (Fig. 8b). These ridges correspond to seismic Unit 5.

259 The shelf seaward of the ridges comprises undulating seafloor defined by NE-
SW striking

260 linear features. These linear features have gentle relief and mimic the contour
of the present13

261 day shoreline. They represent the foresets of seismic Unit 2.2 cropping out on
the seafloor and

262 extending to the continental shelf break (Figs. 3, 4 and 8).

263 The shelf is marked by sinuous to linear seafloor depressions with negative
relief of ~20 m and

264 widths ranging between 400 – 800 m (Figs. 8d and 8e). The seafloor
depressions trend

265 perpendicular to both the ridges and the modern-day shoreline. These
depressions are

266 dominantly asymmetrical U-shaped with gently, across-channel, sloping
floors. The walls and

267 floors of the depressions correspond with seismic Surface 2 and Unit 6.3,
respectively (Figs.

268 4a and 9). Seaward of the ridge features, the depressions terminate in funnel-
like depressions

269 at ~65 m depth (Figs. 8d and 9).

270 The depth structure surface of Surface 2 indicates a clear continuation of
incision of the

271 **Mzimkulu** river and associated tributaries over the continental
shelf towards the
272 shelf break (Fig. 9). Underlying part of Protea Banks is a basement high in the
southern portion
273 of the study area. Basement depressions at stratigraphic depths of 65 m link
up with less
274 pronounced, coast-perpendicular channels which terminate on the outer-
shelf at low-lying sites
275 topped with arcuate spit features, and merge with underfilled valleys and
seafloor depressions
276 (Fig. **8b and c**; 9).

277

278 **4.3. Lithostratigraphy and chronostratigraphy**

279 The basal facies of **Core GeoB20622-2** the sediment core comprises an
approximately 2.5 m
280 thick succession consisting of poorly sorted, very coarse sand with shell
fragments and pebble
281 clasts at the base (Fig. 10). The grain sizes fine upward from very coarse sand
to coarse sand
282 with occasional gritty sub-rounded quartz (Fig. 10). The lower facies
correlates with seismic
283 Unit 6.3 (Fig. 4a and Table 2).

14

284 The lower facies is truncated by a horizontally-orientated quartz pebble layer
and overlain by

285 a 1.4 m thick unit of medium to coarse sand with alternating bands of muddy
sand (Fig. 10a).

286 All the pebbles are homogenous in size with respect to their a- b- and c- axis
(Figs. 10b - d).

287 The a- axes average ~7.5 cm with the b- and c- axes ~5.5 cm and ~3 cm
respectively. **The b-**

288 axis is defined as the maximum horizontal width of the clast (Krumbein,
1939). The angle and

289 orientation of the b-axis of pebbles can provide information on the
depositional environment.

290 All the pebbles rest with their b-axes perpendicular to the seafloor (Fig. 10a).

291 The upper unit is devoid of pebbles. The overall sediment composition of the Unit 6.3 is

292 majority quartz with lesser amounts of feldspar, lithic fragments and bioclastic fragments.

293 (comprising bivalve shell debris, bryozoa and coral). The upper Unit corresponds with seismic

294 Unit 6.3 (Fig. 4a and Table 2). An intact gastropod shell, from the facies boundary that these

295 pebbles mark, yields a ^{14}C age of 1275 ± 301 $191 - 1263$ cal. yr BP. (68% range).

296 Table 2 Summary of core sediment facies and faunal descriptions relative to seismic

297 stratigraphy

Core Facies Thickness Sediment description Fauna Seismic Unit

Lower facies 2.5 m Poorly sorted, very coarse

quartz-rich sand, shell fragments

and pebbles at base. Upward

fining.

Sublittoral

marine taxa (i.e.

echinoderm and

brachiopod)

Unit 6.3

Boundary Quartz pebbles Internal master bedding

plane (Allen, 1982)

Upper Facies 1.5 m Majority quartz with lesser

feldspar and lithic, and

bioclastic fragments. Devoid of

pebbles.

Rounded

calcareous

bioclasts

Unit 6.3

298

299 4.4. Biostratigraphy

300 Core GeoB20622-2The core generally comprises fragmented and abraded
marine sublittoral
301 fauna. The lower facies of the core (at ~361-362 cm depth down core) hosts
fragmented
302 marine taxa (i.e. echinoderms and gastropods), while the upper facies (at
~138-139 cm depth
303 down core) hosts rounded bioclasts of calcareous nature (*Frenzel, P, pers.*
Comm.). These
304 faunae correspondThis lithofacies corresponds to unitUnit 6.3 (Table 2).

305

306 5. Discussion

307 5.1. Seismic Stratigraphy

308 Seismic Unit 1 forms the acoustic basement of the study area and is
considered to correspond
309 to the crystalline basement that crops out along the adjacent shoreline. These
crystalline rocks
310 are overlain by Seismic Unit 2, the seismic architecture of which has been
recognised
311 throughout the region as belonging to seaward-dipping Cretaceous age
siltstones (Green and
312 Garlick, 2011). The capping erosional surface, Surface 2 is considered to
represent the most
313 recent subaerial unconformity (e.g. Green, 2009; Pretorius et al., 2016) that
formed as sea-level
314 fell to the LGM at ~ 125 m depth (Green and Uken, 2005; Cooper et al.,
2018b).

315 Surface 2 reveals that the palaeo-MzimkuluUmzimkulu river incised the
basement rocks during
316 regression associated with the Last Glacial maximum (Fig. 9). The drainage
network bypassed
317 a basement high of Unit 2 in the southern region, indicating a
geomorphological control on the
318 passage of incised valleys across the continental shelf.

319 Seismic Unit 3 is a localised unit found in shallow depressions within Unit 2
at -60 m and at -
320 150 m, respectively. Seismic Unit 3 is comparable to remnant prograding
coastal deposits
321 documented on the mid-shelf and at the shelf edge of the eastern Tyrrhenian
Sea margin
16
322 (Trincardi and Field, 1991). Green (2011) considered similar deposits to the
north of the study
323 area to represent shallow nearshore facies of indeterminable age. Their
preservation appears to
324 be controlled by their location on interfluves and in shallow topographic
depressions which
325 provided shelter from the erosional processes associated with the overlying
wave ravinement
326 surface. Trincardi and Field (1991) proposed that the sheer volume of the
Tyrrhenian Sea
327 deposits was the main factor contributing to their successful preservation.
Their patchy
328 distribution in the study area suggests that they may have been only locally
developed.
329 Unit 4 represents a succession of incised valley fill deposits. The basal
portions of chaotic,
330 discontinuous reflectors (Unit 4.1) represent coarse fluvial channel lags and,
when prograding
331 in a shore-parallel orientation, point bar deposits (cf. Weber et al., 2004;
Green and Garlick,
332 2011; Green et al., 2013b). The capping reflector, Surface 45, delineates the
initial flooding of
333 the fluvial system during the ensuing postglacial transgression and is
interpreted as the
334 transgressive surface (TS) (see Nummedal and Swift, 1987).
335 The mid portions of the valley fills (Unit 4.2) overlie this surface. The sub-
parallel, and, in

336 some cases, horizontal onlapping configurations have been recognized by
many authors as
337 indicative of the central basin fill of a developing wave-dominated (e.g. Zaitlin
et al., 1994;
338 Green et al., 2013b) or mixed wave-tide dominated (Allen and Posamentier,
1994) estuary.
339 Unit 4.2 is capped by an inclined, channel shaped, high amplitude reflector
interpreted as the
340 tidal ravinement surface. (S6). The tidal ravinement surface is best preserved
on the inner-shelf
341 portion whereas a horizontal, flatter high amplitude reflector tops Unit 4.2 on
the outer-shelf
342 segment, if present at all.
343 The upper fill (Unit 4.3) is variable along dip. Horizontal sub-parallel chaotic
discontinuous
344 reflectors indicate a retrogradational character and this unit likely represents
small scale sandy
345 estuarine barriers such as those seen offshore Durban (Nordfjord et al., 2006;
Green et al.,
17
346 2013b) and on the modern coast (Cooper, 2001). This sub-unit represents the
transgressive
347 systems tract of the incised valley fill succession.
348 Unit 5 is a rugged, acoustically opaque unit that crops out on the sea-floor.
This unit is
349 interpreted as cemented aeolianite ridges and barriers of relict shorelines.
These occur at
350 various localities on the southeast African shelf (Martin and Flemming, 1987;
Green et al.,
351 2014; Pretorius et al., 2016). These deposits) and record the depths of past
stillstands during
352 which significant shoreline deposits accumulated. They record shorelines
from depths of -60
353 m and greater (Fig. 11) (Pretorius et al., 2016; Green et al., 2018). Unit 5 and
sub-unitUnit 4.3

354 are capped by the postglacial wave ravinement surface (S7) (see Pretorius et al., 2016).

355 Seismic Unit 6 represents the post-transgressive shoreface and associated sediments that

356 survived wave ravinement processes on the continental shelf. The contemporary shoreface

357 wedge (Sub-unit Unit 6.1) appears as a thin package in the inner-shelf (Martin and Flemming,

358 1986), whereas the offshore sub-unit Unit 6.2 represents palaeo-shoreface deposits that have

359 been decoupled from the contemporary wedge during shoreface translation (Pretorius et al.,

360 2016). Unit 5 deposits act as obstacles that feed back into the shore translation process and

361 inhibit the movement of the complete shoreface as it migrates landward, hence leaving

362 remnants (Unit 6.2) behind. Unit 6.2 deposits are preserved when they are situated in

363 depressions in Unit 5 and are sheltered to a degree from the mid- to outer-shelf current

364 sweeping (Flemming 1980) by the Agulhas Current.

365 Unit 6.3 occurs as thin deposits from the mid-shelf to outer-shelf and as a fill in the underfilled

366 incised valleys of the outer shelf. These fills comprise late Holocene age pebble-floored coarse

367 sand and bioclastic successions. The bioclastic components of the core are wholly composed

368 of marine sub-littoral shell fragments and rounded calcareous clasts. Flemming (1980)

369 observed large to very large dunes forming in coarse sand and fine gravels across this shelf

18

370 region along the east coast of South Africa. Green (2009) observed similar bedforms off the

371 northern KwaZulu-Natal coast and attributed them to current-reworking of
shelf sands and
372 gravels comprising modern highstand sediments.
373 The date obtained from the upper portion of the outermost underfilled incised
valley indicates
374 a maximum age of deposition of 12751191 - 1263 cal. yr B.P, BP (68% range),
which was places
375 sea level within a period metre or two of higher than that of the present sea-
levels in the
376 region day (Fig. 11) (Cooper et al., 2018b). The unit therefore accumulated on
the shelf under
377 conditions similar to present. The horizontally-orientated quartz pebble layers
indicate
378 stratification under current influence associated with the bases of migrating
contemporary shelf
379 subaqueous dune fields (Martin and Flemming, 19922000). These are overlain
by the main
380 dune body of sub-littoral sourced sands and shell debris which have
cascaded into the incised
381 valleys and filled them.
382 The continental shelf, in its entirety, comprises a basement high coinciding
with the ~60 m
383 isobath and resulted in less accommodation space, allowing for dunes to
accrete and
384 concentrate on this portion of the continental shelf. Basement depressions
along the -60 m
385 isobath show a widening of channel systems likely associated with slowstand
events. These
386 depressions may represent low-lying back-barrier estuarine systems that
were overstepped
387 during transgression.
388 **5.5.4. Facies architecture and distribution of incised valley fills across the shelf**
389 The extent and distribution of the incised valley facies varies systematically
across the shelf.

390 In the proximal inner-shelf segment, the fluvial Sub-unitUnit 4.1 makes
upcomprises a large
391 portion of the incised valley-fill (Fig. 12a). Central basin deposits (sub-
unitUnit 4.2) are
392 preserved and capped by tidal ravinement surfaces and then overlain by
sandy barrier and
393 estuarine tidal inlet facies.

19

394 In the mid-shelf region, the incised valley fill succession is comparable to that
of the inner-
395 shelf, although, with increasingly less volumes of fluvial material and an
increase in volume
396 of the central basin fill (Fig. 12b). The barrier facies is separated from the
central basin deposits
397 by a tidal ravinement surface and is capped by the wave ravinement surface.
398 The valleys of the outer-shelf retain a distinctive seafloor depression (Figs.
8d, 8e, 10 and 12c)
399 and are filled at their bases by fluvial materials above which, in the unfilled
valley, they are
400 overlain by materials derived from cascading dunes (Fig. 12c). Payenberg et
al. (2006), show
401 a direct equivalent from Hervey Bay, Australia, where incised valleys on the
shelf are filled
402 with undifferentiated sandy material deposited into an exposed valley by
migrating sub-
403 aqueous dune fields on the contemporary shelf.
404 The absence of the central basin and barrier facies of the transgressive
systems tract in the outer
405 shelf valleys is striking (Fig. 12c). This relative underfilling of the valley during
transgression
406 suggests decoupling from the sea level/sediment supply balance associated
with transgressive
407 filling of estuaries (see Cooper et al., 2012). Such a scenario can occur either
when sea-level

408 rise is rapid (causing an increase in accommodation space) or when either
fluvial or marine

409 sediment supply is significantly reduced. The presence of fluvial deposits in
the valley fill

410 suggests that there was sufficient fluvial supply to the system prior to
transgression. The valley

411 was unfilled during transgression because of a lack of sediment and/or an
increase in

412 accommodation space associated with a rapid increase in sea level.

413 **5.3. Outer-shelf Morphology (shoreline at 100 m below MSL)Mean Sea Level)**

414 The series of aeolianite barriers of Unit 5 (Fig. 2a, 3a, 5b, 5c and 7a), are
separated by small

415 topographic lows (Fig. 8b) and mark a ~ -100 m palaeo-shoreline. The
topographic lows have

416 similar scales and orientations to the modern inlets of barrier-lagoon systems
of SE Africa (cf.

417 Cooper, 2001) and are consequently interpreted as remnants of barrier-inlet
features of the

20

418 palaeo-shoreline. The -100 m palaeo-shoreline is intersected and underlain
by valleys exposed

419 to the seafloor (Unit 4) (Fig. 9). Those valleys terminate in funnel shaped
depressions at -100

420 m. The terminating morphology is identical to the morphology of river-
dominated, microtidal

421 estuaries of southern Africa (cf. Cooper, 1993,1994, 2001) (Fig. 8). Though
large dune fields,

422 intersected by small estuaries, are not evident on the adjacent contemporary
coast, they are

423 common on sediment-rich coasts to both north (Jackson et al., 2014) and
south (Cooper et al.,

424 2013) of the study area. This suggests that past hydrodynamic conditions
were like those of

425 today, however, a larger potential for barrier growth existed when sea levels
were near -100 m.

426 Here, the open shelf, then palaeo-coastal plain, promoted greater wind-
fetches, in addition to
427 greater degree of accommodation whereby larger dunes could be built. In
comparison, as sea
428 level has risen to the modern-day shoreline, the coast has since transformed
into a series of
429 granitic headland-bound embayments and pocket beaches that, due to their
steep and irregular
430 natures, lack sufficient accommodation to allow for large dune building to
occur.

431 The series of arcuate and cusped ridges, together with the seaward
prograded smaller ridges
432 are surface continuations of Seismic Unit 5. Green et al. (2013a; 2014) were
the first to describe
433 such features from the seafloor and considered these to be features of a back
barrier lagoonal
434 shoreline produced by segmentation processes of a coastal waterbody (cf.
Ashton et al., 2009).

435 These ridges co-occur with seafloor depressions and the seaward termination
point of the main
436 Unit 5 barriers, estuaries and inlets. We thus consider them to have formed
simultaneously with
437 the seaward growth, through normal regression, of the -100 m palaeo-
shoreline.

438 The -100 m shoreline corresponds in elevation to sea levels associated with
the Bølling Allerød
439 period when sea level was at ~-100 m (Peltier and Fairbanks, 2006; Green et
al., 2014). Recent
440 work suggests that the LGM involved two periods of sea-level stability
separated by rapid sea-
441 level change (Yokoyama et al., 2018). As discussed by Salzmann et al. (2013),
this general
442 period of sea-level stability was long enough to promote the development of
planform

443 equilibrium shorelines with localised areas of normal regression, forming
444 arcuate back barrier
445 spits and large dune fields in equilibrium with prevailing energy conditions
446 and sediment
447 supply (cf. Ashton et al., 2009).
448 The association of underfilled, incised valleys with this shoreline is notable.
449 As discussed
450 above, these valleys on the outer shelf provide evidence for rapidly rising sea
451 levels that left
452 the outer segments completely drowned in situ. Likewise, we envision the
453 preservation of the
454 associated shorelines to be a result of sea-level rise that led to the rapid up-
455 profile progression
456 of wave ravinement across the continental shelf, leaving less time for the
457 breakdown of
458 shorelines in response to wave action and preserving shoreline deposits by
459 overstepping (*sensu*
460 Swift, 1968). We link this to Melt Water Pulse (MWP) 1-A, which followed the
461 LGM stillstand
462 and was associated with a ~16 m (26–53 mm/yr) rise in sea level between
463 14.6 and 13.8 ka BP.
464 This has been linked to other ~100 m shorelines both locally (Salzmann et al.,
465 2013; Green et
466 al., 2014) and globally (Peltier and Fairbanks, 2006; Liu and Milliman, 2004;
467 Fairbanks, 1989).

456 **5.4. Mid- to Outer-shelf (100 m to 60 m below MSL)**

457 The outer to mid shelf areas (-60 to -100 m) are marked by the cropping-out
458 foresets of Unit
459 2, with no sediment cover or shoreline features (Figs. 2, 3, 5 and 7). Following
460 MWP-1A at
461 13.6 ka cal. B.P. (Peltier and Fairbanks, 2006), the rate of sea-level rise
462 decreased significantly
463 allowing wave ravinement processes to become more effective in eroding and
464 reworking any

existing deposits on the continental shelf (Fig. 12). Coupled with the contemporary erosion by the Agulhas current, and the lack of shelter by aeolianite pinnacles or depressions in the LGM subaerial unconformity, this has led to the complete sediment denudation of these areas by erosion. Other examples of similarly sediment scarce, current swept shelves around the world include the south-eastern shelf of the United States (Harris et al., 2013) and the North Adriatic epicontinental shelf (Trincardi et al., 1994).

22

467

5.5. Mid-shelf (shoreline at 60 m below MSL)

The mid-shelf is marked by a second generation of preserved shoreline complexes at -60 m (Figs. 2, 3, 5 and 7), overlying the LGM-aged incised valleys. Like the -100 m shoreline, remnant submerged shoreline complexes at this depth are prominent along the entire SE African coast (Salzmann et al., 2013; Green et al., 2014; Pretorius et al., 2016; De Lecea et al., 2017). The set of shoals with U-shaped planforms in the shallowest upper portion of the aeolianite field are interpreted as preserved parabolic dune fields (Fig. 8a). Parabolic dunes occur where there are high rates of sediment supply, enough accommodation space to allow for accretion (Oestmo et al., 2014) and strong, unidirectional winds driving sediment transport (Landsberg, 1956). These features indicate southwesterly unidirectional dune migration, as is the case for the majority of parabolic dunes to the north of the study area (Jackson et al., 2014). The gentle

480 relief of the palaeo-coastal plain (as evidenced in the subaerial unconformity)
and the lack of
481 confining headlands accounts for the size of this dune field compared to the
absence of any
482 dune fields in the contemporary coastal setting. The degree to which these
aeolianites are
483 preserved points to rapid supra- and intertidal lithification of the dunes,
commonly seen in
484 subtropical settings (Cooper and Green, 2016). Cooper et al. (2018b) consider
prolonged sea-
485 level stability as a major contributor to the aeolian sediments having longer
residence times in
486 the vadose zone, thus favouring the rapid lithification of dune bases. During
the Younger Dryas
487 Period (~12.8 cal Ka to 11.3 cal Ka), the associated slowstand allowed
enough time for the
488 construction and lithification of a prominent shelf-wide shoreline complex
(Fig. 11) (Pretorius
489 et al., 2016).

23

490 At 11.3 cal Ka, the rate of sea-level rise (13–15 mm/yr) (Liu and Milliman,
2004; Peltier and
491 Fairbanks, 2006; Cooper et al. 2018) is considered to have accelerated
substantially (Green et
492 al., 2014) in response to Melt-Water Pulse 1B (MWP-1B) (Fig. 11). This rapid
rise in sea level
493 lead to the swift overstepping and submergence of the -60 m shoreline now
left relict on the
494 shelf. The aeolianite barriers (Unit 5) and shoreline deposits were partially
eroded and
495 deposited (Unit 6.2) within the hollows between confinement points created
by the aeolianite
496 barriers (Unit 5) (Fig. 7).

497 **5.5.6. Post-transgressive sediment on the shelf**

498 The morphological response of the shoreface to rapid sea-level rise takes
longer than that of
499 adjacent barriers (Swift, et al., 1985; Cooper et al., 2018a), hence the
shoreface retreat lags
500 behind the actual barrier migration (e.g. German Frisian barrier islands,
Flemming and Davis,
501 1994; Fire Island, NY, Sanders and Kumar, 1975). During rapid sea-level rise,
barriers separate
502 from the shoreface leaving it submerged, while the surf- and barrier-zones
migrate rapidly
503 (Cooper et al., 2018a). The barrier then forms a subsequent shoreface by
means of eroding the
504 underlying strata at its new stabilization point (Cooper et al., 2018a). The
original shoreface
505 may remain drowned and stranded on the continental shelf or may continue
to slowly migrate
506 landwards to 'catch-up' with the surfzone and beach system when the sub-
sequent shoreline
507 stabilises (e.g. Beets and van der Spek, 2000; Hijma and Cohen, 2010).
508 Cooper et al. (2018a) point out that reasons for this observed spatially
variable relationship
509 between shoreface and barrier behaviour have not been investigated but may
likely include
510 variability in geological controls and dynamic factors. We consider the mid-
outer shelf pockets
511 of unconsolidated sediment on the seafloor, resting above the wave
ravinement and always in
512 association with shoreline pinnacles to ebbe a good example of this. The -60
m and -100 m
513 barrier shorelines acted as antecedent controls on the up-profile migration of
shoreface
24
514 sediment, thereby restricting and reducing the volume of material available
for the

515 barrier/beach to exchange with landward migration of reworked shoreface
sediment during
516 overstepping. This **leadled** to less sediment available for shoreface
construction as the shoreline
517 migrated landward, thus leaving stranded segments of shoreface deposits on
the outer shelf.
518 Following the assumptions of Davis and Clifton (1987), Pretorius et al. (2016)
showed that on
519 the Durban shelf, rates of shoreface translation were **manifestmanifested** as
changing gradients
520 in the ravinement profile. A steeper ravinement was linked with MWP-1B,
whereas the flatter
521 inner-shelf ravinement was generated by slower rates of sea-level rise
consequent with a
522 considerable slowstand period (Cooper et al., 2018b). A similar scenario is
invoked here. The
523 inner-shelf shows limited preservation of shorelines with a lower gradient
ravinement surface
524 attributed to consequent slower rates of sea-level rise where the shoreface
has managed to catch
525 up the rising sea level.
526 Seaward of the -100 m shoreline outer-shelf, there are few morphological
barriers to cross-
527 shelf sediment transport deeper. Considering that sediments are usually
deposited down profile
528 during transgressive erosion (Pretorius et al., 2017), the transgression from
the -100 m
529 elevation likely shed eroded sediments off-shelf due to the steep and narrow
nature of the
530 region. The finer sediment would also later be entrained southward by the
Agulhas current as
531 bedload leaving winnowed shelf deposits where present.

532 **6. Conclusion**

533 The development of large aeolian dunes on the low-gradient palaeo-coastal
plain of the

534 continental shelf of Protea Banks indicates an open coastal plain palaeo-
setting with an absence

535 of geological controlled coastal compartments in contrast to the
contemporary coast line. The

536 large, unimpeded accommodation space allowed for large dune fields and
open water bodies

537 to develop.

25

538 The two sets of shorelines formed after the LGM and ~~are~~~~were~~ related to
stability of the

539 shoreline during the Bølling Allerød and Younger Dryas periods. We
hypothesize that their

540 preservation, by overstepping, ~~is~~~~was~~ related to the ensuing meltwater pulses
1A and 1B.

541 The Holocene fill architecture of the co-occurring incised valley-fills show
variation from the

542 inner-shelf to the outer-shelf. The outer-shelf incised valleys are
conspicuously under-filled,

543 the fills comprise fluvial deposits truncated by wave ravinement and capped
by contemporary

544 shelf/dune sand deposits. The infill pattern is related to rapid overstepping of
the shoreline due

545 to MWP-1A. The inner shelf valleys conversely reflect a period of relatively
slow sea-level

546 rise which kept pace with sediment supply.

547 We show that during the stepped rises in sea level, the shoreface has
disconnected from the

548 contemporary shoreline. The role of antecedent topography is considered,
together with the

549 rapid rises in sea level, to produce the dislocation and preservation of relict
shoreface sediment

550 on the continental shelf. Given future predictions in sea-level rise, and the
local onshore

551 bedrock controls, a reduction of sediment supply for back-barrier/beach and
shoreface

552 exchange during subsequent shoreline construction could lead to increased
rates of shoreline

553 retreat and potentially overstepping of low-lying coastal areas.

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763 **Figure Captions**

764 **Fig. 1** Locality map illustrating the extent of the bathymetric and seismic data
 collected. The

765 study area is situated seaward of the Umzimkulu River mouth and focuses on the large seafloor

766 shoal of the Protea Banks. Grey lines indicate boomer seismic profiles and blue lines indicate

767 PARASOUND profiles. The red circle indicates the location of **corescore GeoB20622-2**.

768 **Fig. 2** Interpreted shore-perpendicular seismic profile showing underlying Cretaceous strata

769 and capping high amplitude reflector (Surface 2) and prominent ridges of Unit 5 at -60 m.

770 Expanded areas show: a) Rugged Unit 5, capped by erosional Surface 3. b) An incision filled

771 by Unit 4 showing chaotic, discontinuous reflectors. c) A complete incised valley-fill

772 succession comprising Sub-units 4.1, 4.2 and 4.3, capped by an erosional reflector and overlain

773 by Unit 6.3. **S1 - Surface 1 (Sequence Boundary), S2 – Surface 2 (Maximum Flooding Surface)**

774 **and S3 – (Sequence Boundary).**

775 **Fig. 3** Interpreted shore-perpendicular seismic profile. Note the lack of sediment cover above

776 the acoustic basement. Expanded areas show: a) Acoustically opaque Unit 5 onlapped both

777 landward and seaward by **Sub-unitUnit 6.2**, capped by a thin drape of **Sub-unitUnit 6.3**. b) A

778 complete incised valley-fill succession comprising Sub-units 4.1, 4.2 and 4.3, capped by an

779 erosional reflector and overlain by Unit 6.3

780 **Fig. 4** Interpreted shore-perpendicular seismic profile showing incised valley systems on the

781 inner-shelf, together with a ridge of Unit 5 at a depth of 100 m on the outer-shelf. Expanded

782 areas show: a) an incised valley fill succession comprising **Sub-unitUnit 4.1**, truncated by an

erosional surface and overlain by sub-parallel to chaotic reflectors of Sub-unit 6.2. Core

location is indicated by the red line which intersects Sub-unit 6.3 only. b) a PARASOUND

36

shore-parallel interpreted section showing an alternative view to Fig. 4a3a with marked core

location (red line) and a bathymetric depression associated with an underfilled incised valley

and core location (red dot). c) A complete incised valley-fill succession comprising Sub-units

4.1, 4.2 and 4.3, capped by an erosional reflector and overlain by Unit 6.3. Note that Unit 4.3

is truncated by Surface 4, which merges with Surfaces 2 and 3 to form a composite erosional

surface 2/3/4

Fig 5 Interpreted shore-perpendicular PARASOUND profile showing the detailed internal

configuration of the upper seismic units. The expanded areas show: a) Unit 3 resting within a

depression created by Unit 2 and capped by an erosion surface. Unit 6.1 shows sub-parallel to

chaotic reflectors draping the underlying erosional surface. Unit 6.3 drapes over Unit 6.1 with

continuous, semi-parallel reflectors. b) Unit 5, overlapped by sub-units 6.2 and 6.3. Note the

seaward-oblique prograding foresets in Sub-unit 6.2. c) Unit 5 superimposed onto

Cretaceous deposits, capped by an erosional surface and overlapped by Sub-unit 6.2

Fig 6 Interpreted shore-parallel boomer seismic profile showing the inner-shelf sediment. The

expanded areas show: a) Cretaceous basement truncated by an erosional reflector and overlain

800 by the sub-parallel, horizontal reflector package of Sub-unit Unit 6.1. b)
Incised valleys filled

801 by the homogenous, discontinuous and chaotic seismic Unit 4. Sub-unit Unit
6.1 drapes Unit 4.

802 **Fig 7** Interpreted shore-perpendicular boomer seismic profile showing
planation surface

803 truncating Cretaceous strata, superimposed in the outer-shelf region by ridge
features. The

804 expanded areas show: a) Unit 6.2 resting within depressions of Surface 5.
Sub-unit Unit 6.3

805 onlaps both Sub-unit Unit 6.2 and Unit 5. b) Cropping out foresets of Unit 2.1
draped by a thin

806 veneer of Sub-unit Unit 6.1 in the inner-shelf region.

807 **Fig 8** Bathymetry of the study area showing the main morphological features
of the continental

808 shelf. The insets show: a) Parabolic ridges at ~60 m depth. b) Shore-parallel
ridge features. c)

37

809 A pronounced ridge feature with depressions on the seaward and landward
side. Not the 'break'

810 within the feature. d) Plan and cross-sectional view of wide, U-shaped
depressions on seafloor.

811 e) Plan and cross-sectional view of a sinuous sea-floor depression.

812 **Fig 9** Depth structure map of the LGM subaerial unconformity (Surface 2),
depicting the trend

813 of the drainage network from the pre-LGM regression, in relation to the
Umzimkulu river and

814 antecedent topographical highs and lows. Note the correlation with the small
ridges of Unit 5

815 at the shelf edge, together with sinuous seafloor depressions. Vessel lines are
superimposed on

816 Surface 2 as black lines.

817 **Fig 10** Illustration Graphic log of the sampled core corresponding to Sub-unit
6.3 GeoB20622-

818 **2.** The core is dominated by very coarse to coarse, quartz sand interspersed
 with bioclastic
 819 material. The lower section of the core shows a crude upward fining trend in
 grain-size and is
 820 capped with flat-lying quartz pebble layers. The upper most pebble horizon
 yields an age of
 821 1275 ± 30 Cal. yrs B.P. 1191 - 1263 cal yr BP (68% range). The entire core
 comprises layers
 822 of Unit 6.3 separated by an internal master bedding plane (IMBP) indicated
 by the dashed line.

823 Inset a) shows a high-resolution photograph of the pebble horizons in-situ. b)
 and c) Show
 824 rounded oblate quartz pebble obtained from the core. d) Shows a rounded,
 oblate beachrock
 825 pebble. Note the similarity in size of the pebbles.

826 **Fig 11** Relative sea- level curve for the east coast of South Africa from the 12
 20 000 Cal yr
 827 B.P. to present day (after Cooper et al., 20182018b). Grey shading marks
 periods of sea- level
 828 events pertaining to this study. After Cooper et al. (2018).

829 **Fig 12** Interpreted shore perpendicular seismic profiles of incised valley fills
 from different
 830 zones of the shelf. a) The inner-shelf comprising fluvial, central basin and
 estuarine barrier
 831 deposits capped by shelf sand. b) Mid-shelf comprising a higher ratio of
 central basin deposits
 832 to fluvial deposits, topped by estuarine barrier and shelf sand deposits. c)
 Outer-shelf
 38
 833 comprising fluvial sediment overlain by shelf/subaqueous dune sediment. The
 locations of
 834 these valleys are indicated on Figure 1.

835
 836 **Table 1.** Summary of seismic stratigraphic units, separating stratal surfaces
 and interpreted

837 depositional environments.

838 Table 2. Summary of core sediment facies and faunal descriptions relative to
seismic

839 stratigraphy.